

Lepton flavor violating Z-boson decays at GigaZ as a probe of supersymmetry

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Abstract

We briefly review the lepton flavor violating Z-decays at GigaZ as a probe of supersymmetry by focusing on $Z \rightarrow \ell_i \bar{\ell}_j$ in two representative supersymmetric models: the minimal supersymmetric model without R -parity and the supersymmetric seesaw model. We conclude that under the current experimental constraints from LEP and $\ell_i \rightarrow \ell_j \gamma$, these rare decays can still be enhanced to reach the sensitivity of the GigaZ. Therefore, supersymmetry can be probed via these decays at GigaZ.

Keywords: Z-decay, GigaZ, supersymmetry

PACS numbers: 14.80.Ly, 11.30.Fs, 13.66.De

I. INTRODUCTION

The main task of particle physics in the current Large Hadron Collider (LHC) era is probing new physics. The LHC is a powerful discovery machine because of its high energy, but it is not an ideal place for precision test of a theory because of its huge QCD background. If new physics appears at TeV scale, as speculated and expected by most theorists, the LHC will undoubtedly unveil it. Then the proposed International Linear Collider (ILC) will take the task of precision test of such new physics.

At the ILC the GigaZ option is expected to produce more than 10^9 Z-bosons [1] and will play an important role in probing new physics related to Z-boson. One sensitive probe is through the flavor-changing neutral-current (FCNC) Z-boson decays $Z \rightarrow \ell_i \bar{\ell}_j$, which are suppressed to be unobservably small in the Standard Model (SM) but could be greatly enhanced in new physics models like supersymmetry [2–5].

In this review, we recapitulate the studies on the decays $Z \rightarrow \ell_i \bar{\ell}_j$ in the R -parity violating minimal supersymmetric model (RPV-MSSM) [2, 3] and the supersymmetric seesaw model [4]. In Sec.II we delineate the study in RPV-MSSM. In Sec.III we elucidate the study in the supersymmetric seesaw model. Finally, a summery is given in Sec. IV.

II. LEPTON FLAVOR VIOLATING Z-DECAY IN RPV-MSSM

In the MSSM the R -violating interactions are given by

$$\mathcal{W}_R = \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} \epsilon^{abd} U_{ia}^c D_{jb}^c D_{kd}^c + \mu_i L_i H_2, \quad (1)$$

where i, j, k are generation indices, c denotes charge conjugation, a, b and d are the color indices with ϵ^{abd} being the total antisymmetric tensor, H_2 is the Higgs-doublet chiral superfield, and $L_i(Q_i)$ and $E_i(U_i, D_i)$ are the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields. These interactions have rich phenomenology which has been studied intensively [6] and a list of bounds is summarized in [7].

The lepton flavor violating (LFV) processes, which are extremely suppressed in the SM, may be greatly enhanced by these R -violating interactions since both λ and λ' couplings can make contributions. Such R -violating effects in the decays $Z \rightarrow \ell_i \bar{\ell}_j$ and $\ell_i \rightarrow \ell_j \gamma$ were studied in [2, 3, 8]. Taking the presence of λ'_{ijk} as an example, the LFV interactions $\ell_i \bar{\ell}_j V$

($V = \gamma, Z$) can be induced at loop level by exchanging a squark \tilde{u}_L^j or \tilde{d}_R^k , as shown in Fig.1. So far the relevant constraints are from $\ell_i \rightarrow \ell_j \gamma$ given by [9]

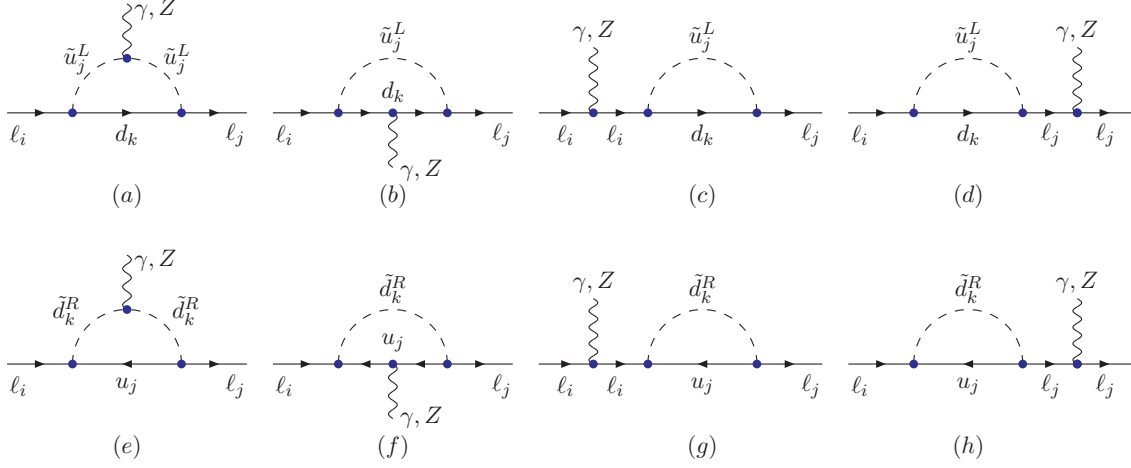


FIG. 1: Feynman diagrams for $\ell_i - \ell_j$ transition induced by L -violating couplings at one-loop level.

$$BR(\mu \rightarrow e \gamma) < 1.2 \times 10^{-11}, \quad (2)$$

$$BR(\tau \rightarrow e \gamma) < 1.1 \times 10^{-7}, \quad (3)$$

$$BR(\tau \rightarrow \mu \gamma) < 4.5 \times 10^{-8}, \quad (4)$$

and the LEP bounds on $Z \rightarrow \ell_i \bar{\ell}_j$ given by [10]

$$BR(Z \rightarrow \mu e) < 1.7 \times 10^{-6}, \quad (5)$$

$$BR(Z \rightarrow \tau e) < 9.8 \times 10^{-6}, \quad (6)$$

$$BR(Z \rightarrow \tau \mu) < 1.2 \times 10^{-5}. \quad (7)$$

The possible sensitivity of GigaZ to the LFV decays of Z -boson could reach [11]

$$BR(Z \rightarrow \mu e) \sim 2.0 \times 10^{-9}, \quad (8)$$

$$BR(Z \rightarrow \tau e) \sim \kappa \times 6.5 \times 10^{-8}, \quad (9)$$

$$BR(Z \rightarrow \tau \mu) \sim \kappa \times 2.2 \times 10^{-8} \quad (10)$$

with the factor κ ranging from 0.2 to 1.0. In Fig. 2 we take $\kappa = 1.0$ to show the sensitivity of GigaZ in RPV-MSSM compared with the bounds from $\ell_i \rightarrow \ell_j \gamma$ and the Z -decays at LEP. We see that under the current experimental constraints, the LFV Z -decays can still be enhanced to the sensitivity of GigaZ. This implies that the GigaZ can further strengthen the bounds on the relevant R-violating couplings in case of un-observation.

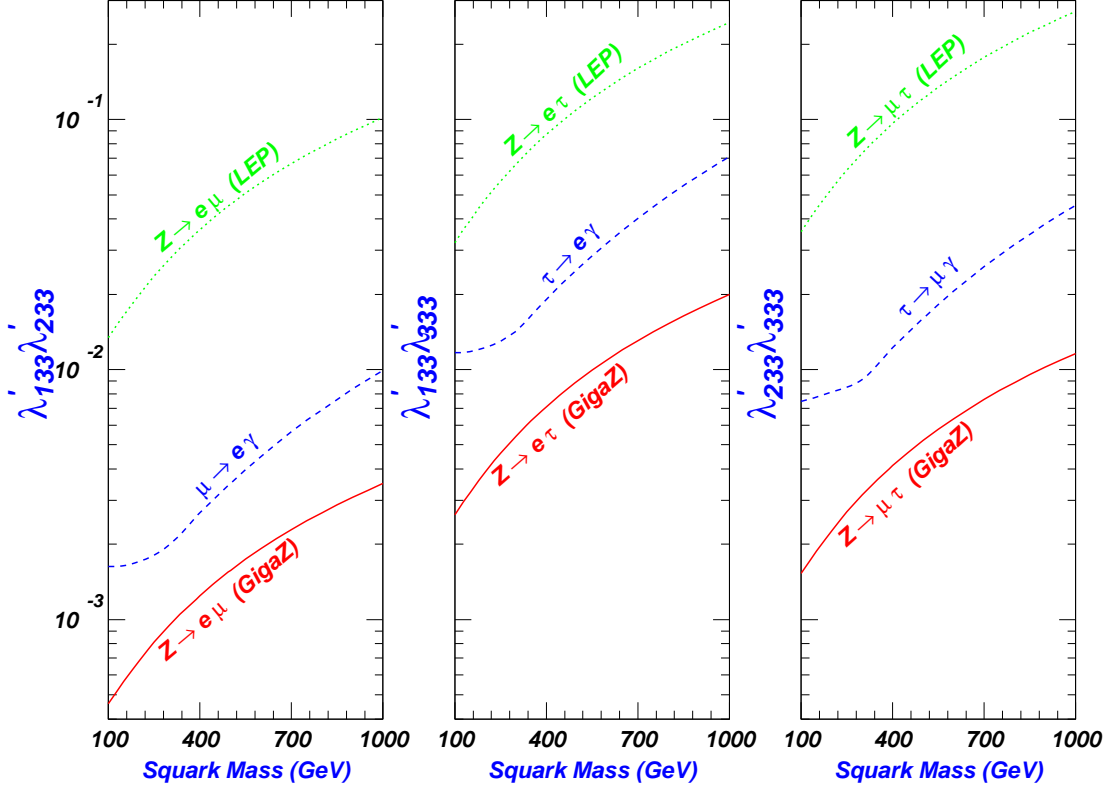


FIG. 2: The 2σ sensitivity of lepton flavor violating Z-decays at GigaZ in RPV-MSSM. Also shown are the bounds from $\ell_i \rightarrow \ell_j \gamma$ and the Z-decays at LEP. These results are taken from [2].

III. LEPTON FLAVOR VIOLATING Z-DECAYS IN SUPERSYMMETRIC SEESAW MODEL

The seesaw mechanism [12] can be realized in supersymmetric models by introducing right-handed neutrino superfields with heavy Majorana masses [13]. In such a framework the flavor diagonality of sleptons is usually assumed at the Planck scale, but the flavor mixings at weak scale are inevitably generated through renormalization equations since there is no symmetry to protect the flavor diagonality. Such flavor mixings of sleptons generated at weak scale are proportional to neutrino Yukawa coupling, which may be as large as top quark Yukawa coupling due to see-saw mechanism, and are enhanced by a large factor $\log(M_P^2/M^2)$ (M_P is Planck scale and M is the neutrino Majorana mass). Therefore, the popular mSUGRA with seesaw mechanism predicts large flavor mixings of sleptons at weak scale.

With the right-handed neutrino superfields ν_R , the superpotential contains the ν_R terms

$$W_\nu = -\frac{1}{2}\nu_R^c \mathbf{M} \nu_R^c + \nu_R^c \mathbf{y}_\nu L \cdot H_2 , \quad (11)$$

where \mathbf{M} and \mathbf{y}_ν are matrices in flavor space, L and H_2 denote the left-handed lepton doublet and the Higgs doublet with hypercharge -1 and $+1$, respectively. The mass matrix of the charged sleptons is given by

$$\mathbf{m}_\ell^2 = \begin{pmatrix} \mathbf{m}_{LL}^2 & \mathbf{m}_{LR}^{2\dagger} \\ \mathbf{m}_{LR}^2 & \mathbf{m}_{RR}^2 \end{pmatrix} \quad (12)$$

with

$$\mathbf{m}_{LL}^2 = \mathbf{m}_{\tilde{L}}^2 + \left[m_\ell^2 + m_Z^2 \cos 2\beta \left(-\frac{1}{2} + s_W^2 \right) \right] \mathbf{1}, \quad (13)$$

$$\mathbf{m}_{RR}^2 = \mathbf{m}_{\tilde{R}}^2 + (m_\ell^2 - m_Z^2 \cos 2\beta \sin^2 \theta_W) \mathbf{1}, \quad (14)$$

$$\mathbf{m}_{LR}^2 = \mathbf{A}_\ell v \cos \beta - m_\ell \mu \tan \beta \mathbf{1}, \quad (15)$$

where $\mathbf{1}$ is unit 3×3 matrix in generation space.

Since the right-handed sneutrinos have a mass as large as the heavy Majorana neutrinos, their contributions to the LFV processes can be ignored. Thus, only the left-handed sneutrinos are needed to take into account, whose mass matrix is given by

$$\mathbf{m}_\nu^2 = \mathbf{m}_{\tilde{L}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta \mathbf{1}. \quad (16)$$

We assume universal soft-breaking parameters at the Planck scale:

$$\mathbf{m}_{\tilde{L}} = \mathbf{m}_{\tilde{R}} = m_0 \mathbf{1}, \quad (17)$$

$$\mathbf{A}_\ell = A_0 \mathbf{y}_\ell, \quad \mathbf{A}_\nu = A_0 \mathbf{y}_\nu .$$

Since \mathbf{y}_ℓ and \mathbf{y}_ν cannot be diagonalized simultaneously in general, it is usually assumed that \mathbf{y}_ℓ is flavor diagonal but \mathbf{y}_ν is not. In this basis the mass matrix of the charged sleptons is flavor diagonal at Planck scale. However, when evolving down through renormalization equations to weak scale, such flavor diagonality is broken:

$$\delta(\mathbf{m}_{\tilde{L}}^2)_{IJ} \simeq -\frac{1}{8\pi^2} (3m_0^2 + A_0^2) (\mathbf{y}_\nu^{0\dagger} \mathbf{y}_\nu^0)_{IJ} \ln \left(\frac{M_P}{\mathcal{M}} \right) , \quad (18)$$

$$\delta(\mathbf{m}_{\tilde{R}}^2)_{IJ} \simeq 0 , \quad (19)$$

$$\delta(\mathbf{A})_{IJ} \simeq -\frac{3}{16\pi^2} A_0 (\mathbf{y}_\ell^0)_{II} (\mathbf{y}_\nu^{0\dagger} \mathbf{y}_\nu^0)_{IJ} \ln \left(\frac{M_P}{\mathcal{M}} \right) , \quad (20)$$

where $\mathbf{y}^0 \equiv \mathbf{y}(M_P)$. Therefore, both the charged sleptons and the left-handed sneutrinos have mixings in flavor space. The flavor mixing of the charged sleptons induces the FCNC couplings $\tilde{\chi}_\alpha^0 \ell_I \tilde{\ell}_J$ and $Z \tilde{\ell}_I \tilde{\ell}_J$, while the flavor mixing of left-handed sneutrinos induces the charged-current flavor-changing couplings $\tilde{\chi}_\alpha^+ \ell_I \tilde{\nu}_J$. These flavor-changing couplings will contribute to the FCNC Z-decays $Z \rightarrow \ell_i \bar{\ell}_j$, as shown in Fig.3.

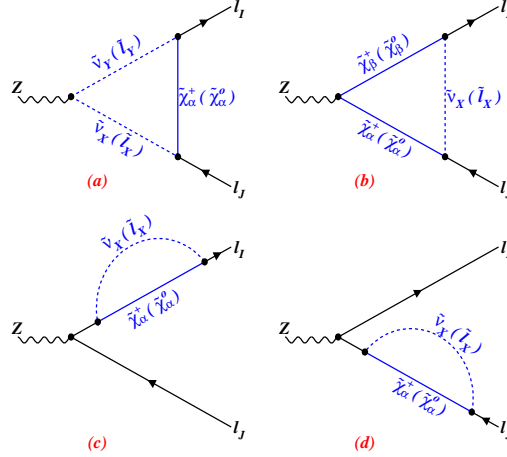


FIG. 3: Feynman diagrams of SUSY contributions to the LFV processes $Z \rightarrow \ell_i \bar{\ell}_j$.

With the constraints from current neutrino oscillation experiments and introducing two right-handed neutrinos with masses $\mathcal{M}_1 = 10^{13}$ GeV and $\mathcal{M}_2 \simeq 10^{15}$ GeV, the branching ratios of $Z \rightarrow \ell_i \bar{\ell}_j$ and $\ell_i \rightarrow \ell_j \gamma$ versus the common scalar mass m_0 are shown in Fig. 4. We see that the branching ratio of $Z \rightarrow \tau \mu$ can reach 10^{-8} in supersymmetric seesaw model (with the current upper bound $BR(\tau \rightarrow \mu \gamma) < 4.5 \times 10^{-8}$ shown in Eq.4, $Z \rightarrow \tau \mu$ with a branching ratio $\sim 10^{-8}$ is allowed, as shown in Fig. 4). Since the GigaZ sensitivity for $Z \rightarrow \tau \mu$ is at 10^{-8} , as shown in Eq.(10), $Z \rightarrow \tau \mu$ may be accessible at GigaZ and thus may serve as a probe of supersymmetric seesaw model.

Note that while the above lepton flavor violating Z-decays serve as a clean probe of new physics at the GigaZ, the FCNC decay modes into quarks such as $Z \rightarrow b \bar{s}$ may also sensitive to new physics. In the SM $Z \rightarrow b \bar{s}$ has a branching ratio of $\sim 10^{-8}$ [14], which could be greatly enhanced in new physics models [15].

IV. CONCLUSION

From the lepton flavor violating Z-decays $Z \rightarrow \ell_i \bar{\ell}_j$ in the R -parity violating minimal supersymmetric model and the supersymmetric seesaw model, we conclude that under the

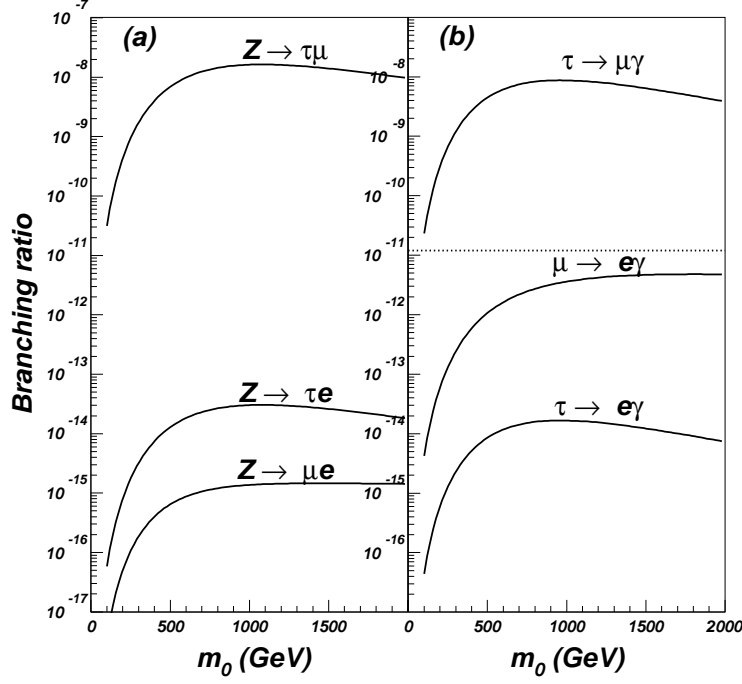


FIG. 4: Branching ratios of $Z \rightarrow \ell_i \bar{\ell}_j$ and $\ell_i \rightarrow \ell_j \gamma$ versus the common scalar mass m_0 [4].

current experimental constraints from LEP and $\ell_i \rightarrow \ell_j \gamma$, these decays can reach the sensitivity of the GigaZ. Therefore, the supersymmetric models can be probed via these decays at GigaZ.

Acknowledgement

Most part of this review was finished while the author was a visiting professor at Henan Normal University. This work was supported by the National Natural Science Foundation of China (NNSFC) under grant Nos. 10821504, 10725526 and 10635030.

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